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Watershed-scale assessment of soil quality in the loess hills of southwest Iowa

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Abstract

Soil quality is a concept that integrates soil biological, chemical and physical factors into a framework for soil resource evaluation. Conventional tillage practices can result in a loss of soil organic matter and decreased soil quality. The potential for soil quality degradation with tillage may vary depending upon landscape position and the spatial distribution of critical soil properties. Information on how to accurately integrate soil spatial information across fields, landscapes and watersheds is lacking in the literature. The primary objective of this study was to evaluate the long-term effect of conventional and ridge-tillage on soil quality in three small watersheds at the Deep Loess Research Station near the town of Treynor in southwest Iowa. Soil types included Monona silt loams in summit positions, Ida or Dow silt loams in backslope positions, and Napier or Kennebec silt loams in footslope positions. We removed surface soil cores from transects placed along topographic gradients in each watershed and quantified total soil organic C (SOC), total soil N (TN), particulate organic matter C (POM-C) and N (POM-N), microbial biomass C (MB-C), N mineralization potential (PMIN-N), nitrate N, extractable P and K, pH, water-stable macroaggregates (WSA), and bulk density (BD). We used terrain analysis methods to group the data into landform element classes to evaluate the effect of topographic position on soil quality. Results indicate that soil quality is higher under long-term ridge-tillage compared with conventional tillage. Soil quality differences were consistently documented among the three watersheds by: (1) quantification of soil indicator variables, (2) calculation of soil quality index values, and (3) comparison of indicator variable and index results with independent assessments of soil function endpoints (i.e. sediment loss, water partitioning at the soil surface, and crop yield). Soil quality differences under ridge-till were found specifically for the backslope and shoulder landform elements, suggesting that soil quality increases on these landform elements are responsible for higher watershed-scale soil quality in the ridge-tilled watershed.
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Keywords: Soil quality; Ridge-till; Terrain analysis; Soil quality index; Watershed

1. Introduction

Evaluation of the soil resource as an integral part of a sustainable agricultural system requires simultaneous multifactor evaluations in order to reflect the total impact of agricultural practices on the environment. Soil quality is a concept that integrates soil biological, chemical and physical factors into a framework for soil resource evaluation (Karlen et al., 1997). The concept of rating soil based on performance is not new and has most often been related to crop productivity. In recent years, the soil quality concept has been broadened to include not only crop productivity, but also environmental sustainability. It has been argued that enhancement of soil quality is a first line of defense against the degradation of water and air quality (Kennedy and

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Papendick, 1995). This argument uses a definition of soil quality that is based on identifying the various functions of soil within an ecosystem (Doran and Parkin, 1994). In this regard, a high quality soil is functioning optimally within the constraints of a given ecosystem. If soil quality is defined only with respect to a soil's capacity to fulfill clearly defined functions, confusion over what constitutes a good quality soil can be avoided (Herrick and Whitford, 1995).

Carbon and nutrient cycling are perhaps the most widely studied ecosystem functions of soil. The partitioning of water at the soil surface and resistance to erosion are equally important soil functions, in part because of their effects on surface and groundwater quality (Warkentin, 1995). Conventional tillage practices, such as moldboard plowing, have been shown to result in the loss of soil organic matter and subsequently, decreased nutrient-supply efficiency. The detrimental effects of tillage on soil are also associated with mixing and redistribution of organic material from the surface of the soil to greater soil depths (Reicosky et al., 1995). This redistribution of organic matter reduces infiltration rates, leading to increased evaporation and decreased water-use efficiency (Mielke et al., 1986; Langdale et al., 1992).

Ecological processes that drive the flow of carbon, nutrients, sediment, and water across and within agricultural landscapes are controlled by complex interactions of soil, plant, and hydrologic parameters. Optimal balance of the ecological processes controlled by these interdependent soil, crop and hydrologic parameters results in high nutrient- and water-use efficiency. In agricultural systems, this is accompanied by subsequent improvements in soil and environmental quality and the maintenance of economically viable crop yields.

Spatial patterns of soil properties are related to differences in soil and ecosystem function. These patterns can be quantifiable attributes of a system and may provide additional information about soil processes (Herrick and Whitford, 1995). Information on how to accurately integrate spatial information across fields, landscapes, and watersheds is lacking in the literature. The use of integrated information, appropriately adjusted for the effects of scale, will improve our ability to accurately evaluate soil quality across landscapes and to assess the concomitant effects on surface and groundwater water quality.

Currently, there is a need for experimental approaches that integrate information collected from fields and landscapes to represent outcomes measured at the watershed scale. Our primary objective was to evaluate the long-term effect of conventionally and ridge-tillage managed continuous corn on soil biological, chemical and physical parameters within three field-sized watersheds located in the loess hills of southwest Iowa. Our secondary objectives were to investigate the feasibility of using terrain analysis methods and the Soil Management Assessment Framework (SMAF) to perform watershed-scale assessments of soil quality.

2. Materials and methods

2.1. Field site description and agricultural management

Our research site is located at the Deep Loess Research Station near Treynor, IA. The research station was established by the USDA-ARS to study the impact of agronomic practices on runoff and water-induced soil erosion. Hydrologic characteristics of the site are representative of the deep loess hills located in western Iowa and northwestern Missouri. In 1964, three small, field-size watersheds, ranging in size from 27.7 to 43.3 ha, were delineated based on hydrologic function. Two of the watersheds (Watersheds 1 and 2) were cropped to continuous corn (*Zea mays* L.) from 1964 to 1995. The third watershed (Watershed 3) was used for cattle grazing from 1964 to 1972 and converted to continuous corn production in 1972 (Fig. 1).

Soils at summit positions are Monona silt loams (FAO, Haplic Phaeozems; USDA, fine-silty, mixed, superactive, mesic Typic Hapludolls). Ida or Dow silt loam soils (FAO, Calcaric Regosols; USDA, fine-silty, mixed, calcareous, mesic Typic Udorthents) are found in backslope positions and footslope soils are Napier or Kennebec silt loams (FAO, Cumulic Haplic Phaeozems; USDA, fine-silty, mixed, superactive, mesic, Cumulic Hapludolls) (Logsdon et al., 1999).

Watersheds 1 and 2 were farmed on the contour using conventional tillage and planting methods. Primary conventional tillage was accomplished with a moldboard plow until the early 1980s and by deep disking thereafter through 1995. Field cultivation or

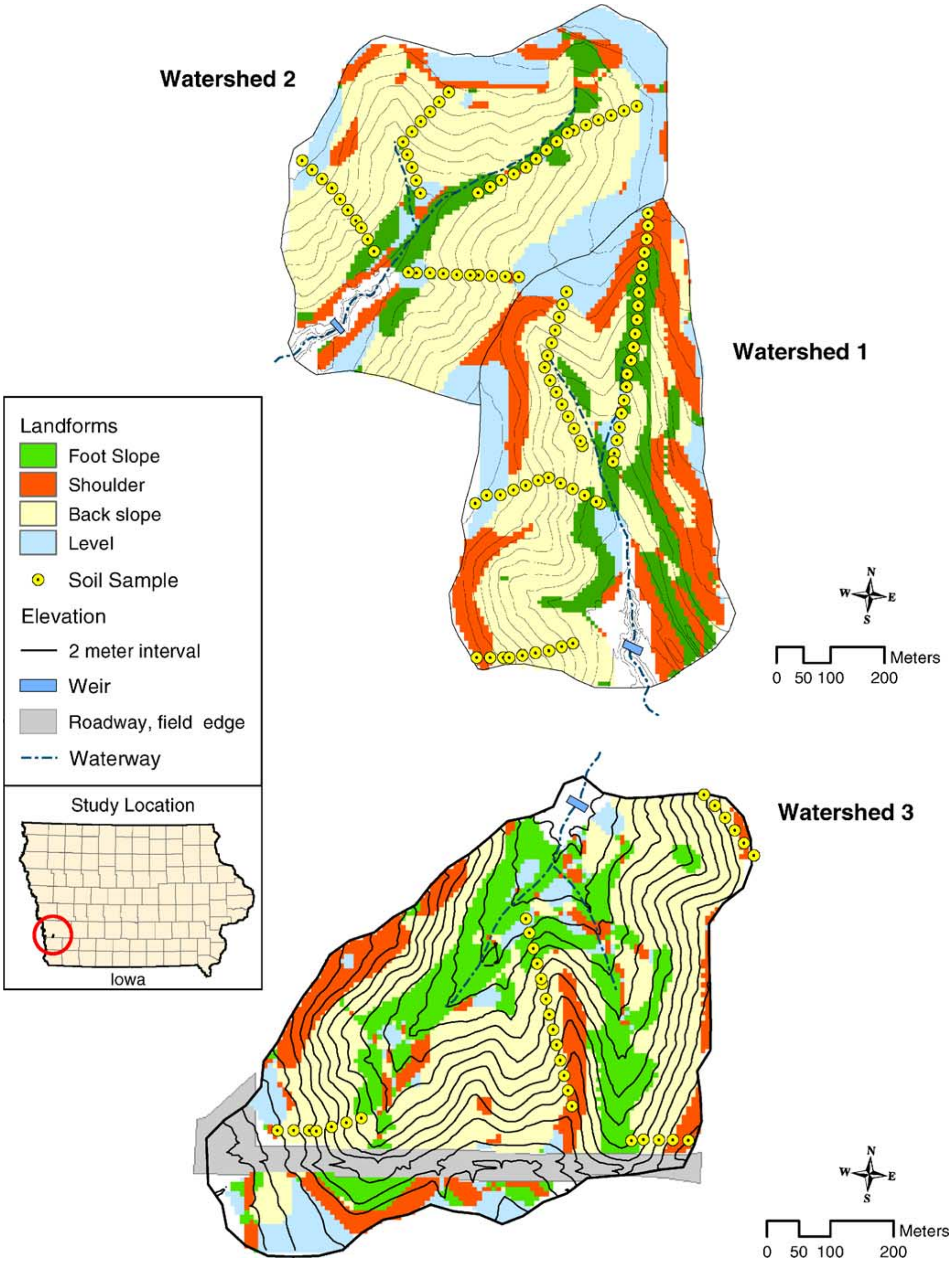

Fig. 1. The distribution of landform elements and soil sampling transects in the three watersheds. The sampling positions represent $7.5\,\mathrm{m} \times 7.5\,\mathrm{m}$ cells on the DEM and are not drawn to scale. The map was constructed using a despeckling routine to produce a general representation of the landform elements. We further subdivided the level landform element shown in the figure into summits (level landform elements in upland positions) and toeslopes (level landform elements in lowland positions) on the basis of elevation.

shallow disking was used for seedbed preparation. Prior to 1972, Watershed 3 was predominantly a bromegrass (*Bromus inermis* L.) pasture, with smaller amounts of orchardgrass (*Dactylis glomerata* L.) and alfalfa (*Medicago sativa* L.). In 1972, Watershed 3 was converted to ridge-tillage management for continuous corn production. There was no pre-plant tillage and the seedbed was created at planting using a Buffalo ridge-till planter (Fleischer Manufacturing Inc., Columbus, OH).[1] Annual fertilizer N application rates ranged from 112 to 478 kg ha^{-1} for Watershed 1, 114 to 237 kg ha^{-1} for Watershed 2, and 124 to 198 kg ha^{-1} for Watershed 3 (Karlen et al., 1999).

2.2. Field sampling

Corn grain yield was determined by hand-harvesting at summit-shoulder, backslope, and footslope–toeslope positions within each watershed from 1972 to 1995. Twelve sampling locations (i.e. yield plots) were distributed within each watershed based on soil series, slope, and erosion class. The location of each yield plot within the watersheds was consistent from year to year (Karlen et al., 1999).

Within each of the three watersheds, yield plot locations were used to anchor four soil sampling transects that were placed on the landscape after corn harvest in 1994 and 1995. Generally, transects began on the hilltops or shoulders and ended on the toeslopes. Soil cores were taken to a depth of 15 cm using a truck-mounted Giddings® (Giddings Machine Company, Ft. Collins, CO) soil sampler every 25 m along each transect. Two 7.6 cm diameter cores were taken at each location and combined into one composite sample from each location. Additional cores were taken by hand to 15 cm for measurement of bulk density. Soil samples were placed in zip-lock bags, stored in insulated chests in the field, kept cool during transport to the laboratory, and stored at 4 °C in the laboratory until analysis. Sampling locations were marked and referenced by survey methods to benchmark locations within the watersheds. These data were later converted into a georeferenced database maintained using ArcInfo GIS software.

A digital elevation model (DEM) was developed for each of the watersheds from aerial photographs of the landscape. The DEM was processed to derive primary and secondary terrain attributes and the terrain attributes were aggregated to derive landscape elements. The soil sampling locations were assigned to one of the five landform element classes by overlaying the DEM with the georeferenced soil locations (Fig. 1). The five landform element classes used in this study were summit, shoulder, backslope, footslope, and toeslope. The majority of the data were processed using ArcInfo GIS software, version 7.1.1 (Environmental Systems Research Institute, Redlands, CA). Further details of DEM development can be found in Moorman et al. (2004).

2.3. Laboratory methods

Bulk density in the field was estimated using the oven-dried soil mass and the field volume of the sample (Blake and Hartge, 1986).

Field-moist samples were pushed through an 8 mm diameter sieve and soil water content was determined gravimetrically after oven drying overnight at 105 °C. A sub-sample was pushed through a 2 mm diameter sieve, air-dried and stored at room temperature prior to analysis. Field-moist 8 mm sieved soil sub-samples were extracted with 2 M KCl (Gelderman and Beegle, 1998), and inorganic N [(NO_3+NO_2) and NH_4] in the filtrate was determined using flow injection technology (Lachat Instruments, Milwaukee, WI). Microbial biomass C (MB-C) was measured by fumigation and direct extraction with 0.5 M K_2SO_4 on 8 mm sieved field-moist samples (Tate et al., 1988). Organic C in the fumigated and non-fumigated extracts was measured using a Dohrmann DC-180 carbon analyzer (Rosemount Analytical Services, Santa Clara, CA) and biomass C was calculated using the correction factor ($k = 0.33$) of Sparling and West (1988). Soil organic C (SOC), total N (TN), particulate organic matter C (POM-C) and N (POM-N), N mineralization potential (PMIN-N), extractable P and K and pH were determined for the air-dried 2 mm sieved soil samples. Total SOC (after removal of carbonates with 1 M H_2SO_4) and TN were measured using dry combustion methods in a Carlo-Erba NA1500 NCS

[1] Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the US Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

elemental analyzer (Haake Buchler Instruments, Paterson, NJ). Particulate organic matter was isolated and POM-C and POM-N were quantified according to methods described by Cambardella and Elliott (1992) using dry combustion. Potentially mineralizable N was measured using an aerobic 28-day incubation method described by Drinkwater et al. (1996). Phosphorous concentrations (Bray-P) (Frank et al., 1998) were measured colorimetrically using ascorbic acid–ammonium molybdate reagents. Exchangeable K was extracted with 1 M ammonium acetate (Warnecke and Brown, 1998) and measured using atomic absorption spectrophotometry. Soil pH (Watson and Brown, 1998) was measured using a 1:2 soil-to-water ratio.

Aggregate stability was assessed for 8 mm sieved, air-dried samples according to the methods described by Cambardella and Elliott (1993) and expressed as the percentage of the total soil that was water-stable macroaggregates greater than 250 μm in diameter (WSA).

All results are expressed on a dry weight basis. Most measurements were converted to volumetric units using sample bulk densities.

2.4. Soil Management Assessment Framework methods

We used the Soil Management Assessment Framework to calculate soil quality index values (Andrews et al., 2002) for the three watersheds. We used SOC, TN, POM-C, POM-N, MB-C, PMIN-N, nitrate N, WSA, P, K, pH and BD as soil quality indicator variables for this calculation. Soil indicator values were transformed with non-linear scoring curves to unit-less scores that reflect performance of soil functions, using CurveExpert, version 1.3 shareware[1] (http://www.ebicom.net/∼dhyams/cvxpt.htm). Some important soil functions (or ecosystem services) include: water and solute retention and flow, physical stability and support; retention and cycling of nutrients; buffering and filtering of potentially toxic materials; and maintenance of biodiversity and habitat (Daily, 1997). For each scoring curve, the *y*-axis was a unit-less 0–1 functional performance value. The *x*-axis represented the expected range for each soil indicator. The shape of each scoring curve, typically some variation of a bell-shaped curve ('mid-point optimum'), a sigmoid curve with an upper asymptote ('more is better'), or a sigmoid curve having a lower asymptote ('less is better') (Karlen and Stott, 1994), represented the indicator's relationship to soil function, which was determined by literature review and consensus of the collaborating researchers. Individual indicator scores were then summed to create an additive index of soil quality. Higher index scores indicate better soil quality. Further information about the theory and development of the SMAF can be found in Andrews et al. (2002).

2.5. Statistical analysis

Preliminary analysis indicated the soil data were non-normally distributed. Therefore, non-parametric statistics (Wilcoxon analysis with Kruskal–Wallis test) were used to test for significant differences among watersheds or landform elements at $\alpha = 0.05$. Analysis of variance using parametric methods on log-transformed data yielded similar results to the non-parametric analysis. Type III sums of squares were used in the parametric ANOVA. Means were separated using Duncan's multiple range test at $P = 0.05$ (SAS Institute, 1992). For soil quality index values, means for the watersheds and landscape positions were compared with ANOVA for unbalanced design and Student's *t* means comparison test at $P \leq 0.05$ using JMP®, version 3, for Windows (SAS Institute, Cary, NC).

3. Results and discussion

3.1. Tillage effects on soil properties

There were statistically significant differences among the three watersheds in SOC and TN (Table 1). Watershed 3, managed with ridge-tillage for 24 years, had more SOC and TN in the top 15 cm of soil than the two watersheds under conventional tillage. Ridge-tillage management resulted in an average of 213 kg ha^{-1} per year more C than conventional deep-disk tillage under continuous cropping to corn. Quantities of TN in the surface soil were also greater in Watershed 3 than in the two conventionally tilled watersheds. Absolute amounts of SOC and TN were lowest in Watershed 2, although the difference was not statistically significant for SOC.

Table 1
Surface soil properties for three watersheds averaged across landform elements

Soil component	Watershed[a]		
	W1	W2	W3
SOC (Mg C ha^{-1})	25.2 b[b]	24.0 b	29.7 a
TN (Mg N ha^{-1})	2.6 b	2.31 c	2.9 a
POM-C (Mg C ha^{-1})	5.9 b	5.0 c	7.0 a
POM-N (Mg N ha^{-1})	0.98 a	0.26 c	0.49 b
MB-C (Mg C ha^{-1})	0.47 a	0.44 a	0.47 a
PMIN-N (Mg N ha^{-1})	0.054 b	0.049 b	0.062 a
Nitrate N (Mg N ha^{-1})	0.038 a	0.010 b	0.011 b
WSA (%)	18.1 b	11.5 c	24.0 a
P (mg P kg^{-1})	47 a	25 b	24 b
K (mg K kg^{-1})	201 a	186 ab	173 b
pH	5.3 b	6.0 a	5.9 a
Bulk density (g cm^{-3})	1.11 a	1.12 a	1.06 b
Yield (Mg ha^{-1})	7.7 ab	7.5 b	8.0 a

[a] Mean for the top 15 cm of soil, based on 53 observations for W1, 57 for W2, and 51 for W3. Deep-disk tillage was used in W1 and W2 and ridge-tillage in W3.

[b] Non-parametric Wilcoxon analysis with Kruskal–Wallis test; mean differences separated by Duncan's test at $P \leq 0.05$. Means in the same row followed by the same letter are not significantly different.

The surface soil of Watershed 1 had statistically more extractable P and K than Watersheds 2 and 3. Extractable P and K concentrations ranged from 24 to 47 and 173 to 201 mg kg^{-1}, respectively, for the three watersheds. Soil pH was slightly acidic in all three watersheds, ranging from 5.3 in Watershed 1 to 6.0 in Watershed 2. Soil pH was significantly lower in Watershed 1 compared to the other two watersheds. Watershed 1 also had significantly more nitrate N in the top 15 cm of soil. Long-term total N fertilizer application rate from 1972 to 1995 was 7359, 5696, and 4581 kg N ha^{-1} for Watersheds 1, 2 and 3, respectively (Karlen et al., 1999), suggesting the lower pH for Watershed 1 may be related to long-term application of nitrogen fertilizer.

Soils managed with ridge-tillage (Watershed 3) contained higher amounts of POM-C, PMIN-N, and WSA relative to soils in the conventionally tilled watersheds (Table 1). Amounts of MB-C did not differ among the watersheds. Microbial biomass C, POM-C, PMIN-N, and WSA are important forms of biologically active soil organic matter. Amounts of biologically active soil organic matter are affected by tillage practices and other forms of soil disturbance (Cambardella and Elliott, 1992; Reicosky et al., 1995; Drinkwater et al., 1996; Rice et al., 1996; Frey et al., 1999). Although Watershed 3 soils contained more of the active forms of carbon than the other watersheds, the quantities of POM-C, PMIN-N and MB-C as proportions of total SOC in Watershed 3 are similar to the other two watersheds. Particulate organic matter C accounted for 20.8–23.5% of SOC while MBC accounted for 1.6, 1.9, and 1.8% of total SOC in Watersheds 3, 1 and 2, respectively. Potentially mineralized N, expressed as a percentage of soil TN, ranged from 2.08% in Watershed 1 to 2.14% in Watershed 3. The fact that POM-C, MB-C, and PMIN-N constitute relatively constant fractions of the total SOC and TN, suggests these soil components are largely in equilibrium with organic inputs from crop production and the larger organic matter pools in these soils.

The ratio of MB-C to SOC has been proposed as an indicator of organic C accrual or loss (Anderson and Domsch, 1989; Sparling, 1992). Sparling (1992) found MB-C dropped from 2% of total SOC in a pasture soil to approximately 1.4% in the same soil cropped to continuous corn for 12 years, which indicated a decline in soil quality. We do not have data on MB-C from 1972, but the percentage contribution of MB-C in all three watersheds is small compared to other published values.

Macroaggregation is a soil quality indicator that is positively related to the physical protection of organic matter, improved water infiltration, and reduced soil erosion (Boyle et al., 1989; Balesdent et al., 2000; Rhoton et al., 2002). Since macroaggregates tend to decline as tillage intensity increases (Cambardella and Elliott, 1993; Rhoton et al., 2002), the increased level of macroaggregation in Watershed 3 soil compared to the other watersheds probably reflects the lower intensity of tillage in Watershed 3.

3.2. Soil quality assessment for different landform elements

Analysis of soil quality parameters among the landform elements revealed additional information about the spatial distribution of soil properties across the three watersheds. There is evidence for soil movement within these small watersheds with soil erosion occurring in the backslope and shoulder positions and soil deposition in footslope and toeslope positions

Table 2
Surface soil properties for different landform elements averaged across watersheds

Soil component[a]	Landform				
	Toeslope	Footslope	Backslope	Shoulder	Summit
SOC	29.1 a[b]	27.9 a	25.3 a	25.8 a	28.7 a
TN	2.73 a	2.82 a	2.49 a	2.60 a	2.97 a
POM-C	6.08 b	7.77 a	5.79 b	4.86 b	5.54 b
POM-N	0.43 b	0.90 a	0.56 b	0.42 b	0.57 b
MB-C	0.46 a	0.53 a	0.45 a	0.41 a	0.46 a
PMIN-N	0.064 a	0.061 ab	0.052 b	0.055 ab	0.065 a
Nitrate N	0.017 a	0.031 a	0.018 a	0.017 a	0.025 a
WSA	11.7 a	21.3 a	17.0 a	20.6 a	15.5 a
P	31 a	41 a	31 a	27 a	37 a
K	247 a	202 ab	176 b	172 b	241 a
pH	6.0 ab	6.1 a	5.8 ab	5.3 bc	4.9 c
BD	1.10 a	1.11 a	1.10 a	1.07 a	1.09 a

[a] To a depth of 15 cm. Units are $Mg\,ha^{-1}$ for SOC, TN, POM-C, POM-N, MB-C, PMIN-N, and nitrate N; percentage of total soil mass as macroaggregates (>250 μm in diameter) for WSA; $mg\,kg^{-1}$ for P and K; and $g\,cm^{-3}$ for BD.
[b] Non-parametric Wilcoxon analysis with Kruskal–Wallis test; mean differences were separated by Duncan's test at $P \leq 0.05$. Means in the same row followed by the same letter are not significantly different.

(Kramer et al., 1999; Moorman et al., 2004). Data trends show SOC ($P = 0.1517$) and TN ($P = 0.0612$) were lower for the backslope and shoulder elements and greater for the footslope, toeslope and summit elements (Table 2), although differences among the landscape elements were not significant at the 95% probability level. Other researchers have reported similar patterns of carbon distribution among landscape elements (Schimel et al., 1985; Wood et al., 1990; Pennock et al., 1994; Gregorich et al., 1998). Particulate organic matter C was higher in footslope and toeslope soils than in backslope, shoulder and summit soils, but the difference was significant only for the footslope soils. Potentially mineralizable N was lower for the backslope and higher for the footslope, toeslope and summit landscape elements but the difference was not statistically significant for the backslope/footslope comparison. Microbial biomass C and WSA did not differ among the five landform elements, although absolute values for both parameters were highest in the footslope position (Table 2).

Mean extractable soil P concentrations for the five landscape element classes ranged from 27.3 to $41.4\,mg\,P\,kg^{-1}$, and there were no significant differences among element classes. Backslope and shoulder elements had statistically less extractable soil K than the other three landform element classes. Soil pH was acidic, ranging from 4.9 to 6.1 for summit and footslope soils, respectively. Soil pH was significantly lower for the summit landform element relative to the other four landform element classes. There was no difference in the amount of soil nitrate N among the landform elements, although footslopes had the highest numeric level of soil nitrate N (Table 2).

Soil quality assessment among the landform elements using the SMAF showed that soil quality is statistically higher in footslope soils than in backslope and shoulder soils (Fig. 2). Similarly, long-term average corn yield (1972–1995) for the three watersheds is lowest in the backslope position and highest in the footslope and toeslope positions (Table 3). Crop yield is an important soil function endpoint commonly applied to agricultural systems (Andrews et al., 2002). Soil and long-term crop yield data support the hypothesis that soil quality is higher in depositional areas of the landscape and lower in the areas more prone to erosion.

The hypothesized differences in soil quality can occur as a direct result of erosion processes but can also occur because of differences in the rate of decomposition of soil organic matter and organic inputs within the various landform elements. For instance, soil moisture levels as predicted by the wetness index described in our companion paper (Moorman et al., 2004) are relatively higher in depositional landscape positions

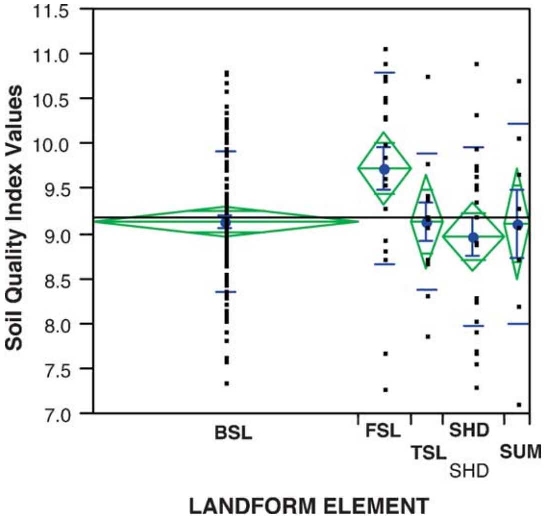

Fig. 2. Soil quality index values for each landform element (BSL: backslope; FSL: footslope; TSL: toeslope; SHD: shoulder; SUM: summit) averaged across all three watersheds ($P < 0.09$). The diamonds show descriptive statistics for each landform element. The line across each diamond represents the landform element mean. The height of each diamond represents the 95% confidence interval for each landform element, and the diamond width represents a relative measure of group sample size. Bars are 1 and 2 standard errors from the mean (filled circle at center of mean diamond). The horizontal black line across the entire graph is the total response sample mean.

compared to backslopes and shoulders, and as a result, soil temperature is lower. Rates of microbial decomposition are slower under cooler, wetter soil conditions thereby favoring SOC accumulation.

Table 3
Long-term average yield for landform elements averaged across watersheds

Landform element	Yield[a]	Normalized yield[b]
Toeslope	8.2 a[c]	1.1 a
Footslope	8.3 a	1.1 a
Backslope	7.5 b	1.0 b
Shoulder	7.9 ab	1.0 b
Summit	7.7 ab	1.0 b

[a] Corn yield in $\mathrm{Mg\,ha^{-1}}$.

[b] For each year from 1972 to 1995, yield at each location divided by mean watershed yield.

[c] Non-parametric Wilcoxon analysis with Kruskal–Wallis test; mean differences were separated by Duncan's test at $P \leq 0.05$. Means in the same column followed by the same letter are not significantly different.

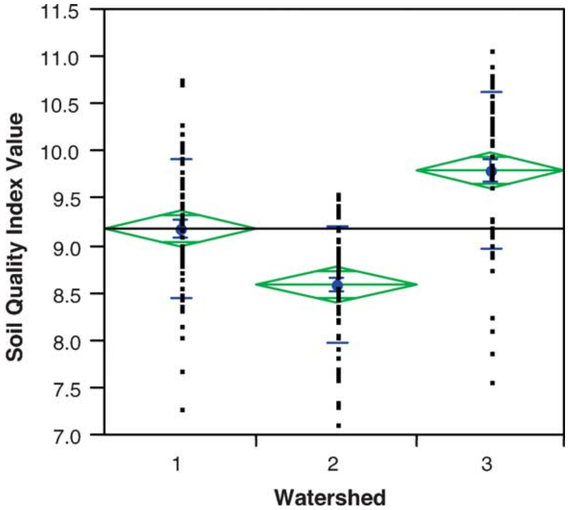

Fig. 3. Soil quality index values for sample points in each watershed averaged across all landform elements ($P < 0.001$). The diamonds show descriptive statistics for each watershed. The line across each diamond represents the watershed mean. The height of each diamond represents the 95% confidence interval for each watershed, and the diamond width represents a relative measure of group sample size. Bars are 1 and 2 standard errors from the mean (filled circle at center of mean diamond). The horizontal black line across the entire graph is the total response sample mean.

3.3. Watershed-scale soil quality assessments

Watershed-scale assessment of soil quality index values (Fig. 3) and soil function endpoints (i.e. sediment loss, water partitioning at the soil surface, and crop yield) shows that soil quality significantly differs among the three watersheds. Total sediment yield is lower (Moorman et al., 2004), infiltration is higher (Kramer et al., 1999), and long-term average corn yield (Table 1) is greater in Watershed 3 than in the two conventionally tilled watersheds. At this location, long-term ridge-tillage has maintained a relatively higher level of soil quality, as evidenced by greater amounts of SOC and biologically active fractions of soil organic matter (Table 1), than under conventional tillage management.

Significant differences in soil quality between Watersheds 1 and 2 are more difficult to explain. Terrain analysis shows that Watershed 1 is more steeply sloping than Watershed 2 (Karlen et al., 1999). The steeper slopes result in slightly more water being partitioned into runoff and, subsequently, higher runoff

Table 4
Distribution of landform elements within three watersheds

Landform element	Watershed[a]		
	W1	W2	W3
Toeslope	7.2	18.3	6.5
Footslope	20.2	12.4	18.0
Backslope	43.5	49.3	46.1
Shoulder	22.0	14.0	23.0
Summit	7.2	6.1	6.5

[a] Percent of watershed area.

may lead to higher sediment loss (Kramer et al., 1999). Our companion study reports SOC levels measured in 1972 for Watershed 1 (28.1 Mg C ha^{-1}) were relatively close to SOC levels measured for Watershed 3 (23.9 Mg C ha^{-1}) in 1995 (Moorman et al., 2004). Furthermore, they report that total SOC in Watershed 2 decreased by nearly 50% between 1972 and 1995, but Watershed 1 SOC loss for the same time period was only 10%. This suggests soil quality may have been different in the two watersheds in 1972, even though they had been under the same agricultural management practices for the 8 years previous to 1972. Since Watershed 1 SOC levels changed little between 1972 and 1995, soil quality in this watershed may have already been at equilibrium with respect to conventionally tilled continuous corn in 1972. Soil quality in Watershed 2, however, may have still been declining.

Terrain analysis methods based on DEM facilitated the comparison of soil factors among the five landform elements. We hypothesized that soil quality would be different among the landform elements since sediment loss and deposition has occurred in these watersheds. We observed that overall soil quality based on measured differences in soil properties (Table 2) and calculated differences in soil index values using the SMAF (Fig. 2), was generally lower for the backslope and shoulder landform elements and generally higher for the footslope and lowland landform elements when the data were averaged across the three watersheds. In order to refine our assessments of watershed-scale soil quality, we used our GIS database to estimate the relative area within the watersheds represented by each of the five landform elements (Table 4). The areal distribution of the five landform elements within the watersheds is unequal. Backslope and shoulder elements occupy more than twice the watershed area than footslope and toeslope elements (Table 4). Therefore, depositional processes have led to increased soil quality across a relatively small landscape area. Erosional processes have reduced soil quality across more than 60% of the total area in the three watersheds (Kramer et al., 1999; Moorman et al., 2004).

Further analysis to evaluate soil quality differences among the landscape elements within each individual watershed was carried out to refine our

Table 5
Surface soil properties and SMAF outcomes for different landform elements within each watershed[a]

Soil property/landform element	Watershed		
	W1	W2	W3
SOC (Mg C ha^{-1})[b]			
Toeslope	26.9 a	28.9 a	32.0 a
Footslope	25.4 b	21.1 b	35.5 a
Backslope	25.3 b	22.7 b	28.4 a
Shoulder	23.1 a	25.0 a	28.0 a
Summit	25.6 b	25.4 b	38.1 a
POM-C (Mg C ha^{-1})			
Toeslope	5.34 a	5.67 a	8.47 a
Footslope	7.12 a	5.38 a	9.66 a
Backslope	5.84 ab	5.19 b	6.44 a
Shoulder	5.33 a	3.42 b	5.87 a
Summit	4.31 b	4.13 b	9.49 a
PMIN-N (Mg N ha^{-1})			
Toeslope	0.0564 a	0.0641 a	0.0712 a
Footslope	0.0619 a	0.0430 a	0.0699 a
Backslope	0.0509 b	0.0456 b	0.0592 a
Shoulder	0.0508 a	0.0513 a	0.0592 a
Summit	0.0615 b	0.0550 b	0.0872 a
WSA (%)			
Toeslope	10.6 b	9.5 b	20.3 a
Footslope	22.7 a	12.5 a	23.6 a
Backslope	16.6 b	12.2 c	23.1 a
Shoulder	22.5 a	10.9 b	28.3 a
Summit	17.2 a	9.2 a	22.5 a
Soil quality index value			
Toeslope	9.3 a	9.1 a	9.3 a
Footslope	9.4 ab	8.9 b	10.5 a
Backslope	9.1 b	8.6 c	9.8 a
Shoulder	9.3 ab	8.3 b	9.5 a
Summit	9.3 ab	8.1 b	10.4 a

[a] Non-parametric Wilcoxon analysis with Kruskal–Wallis test; mean differences were separated by Duncan's test for SOC, POM-C, PMIN-N and WSA and Student's t for soil quality index values, both at $P \leq 0.05$. Means in the same row followed by the same letter are not significantly different.

[b] To a depth of 15 cm.

watershed-scale assessments discussed in previous paragraphs. Soil organic C, POM-C, PMIN-N, water-stable macroaggregation and soil quality index values for the backslope and shoulder landscape elements were significantly greater in the ridge-tilled watershed than in the conventionally tilled watersheds (Table 5). In general, the differences among the three watersheds for soil quality parameters in the footslope and lowland level depositional areas of the landscape were minor. This suggests increases in soil quality at the backslope and shoulder positions are responsible for the overall higher soil quality observed for Watershed 3. There were significantly greater amounts of water-stable macroaggregates for the backslope and shoulder positions and a significantly higher soil quality index values in the backslope position in Watershed 1 relative to Watershed 2 (Table 5). This information indicates that degradation of the aggregate structure is selectively occurring at these two landscape positions in Watershed 2 and may be substantially contributing to the degradation of soil quality in this watershed.

4. Conclusions

This study evaluated the long-term effect of conventionally and ridge-till managed continuous corn on soil biological, chemical and physical parameters within three field-sized watersheds located in southwest Iowa. The results indicate soil quality under ridge-tillage was higher than under conventional deep-disk tillage in these loess-derived soils. Amounts of total and biologically active soil organic matter, infiltration, long-term average corn yields, and soil quality index values were all greater and sediment loss was lower under ridge-tillage at the watershed scale. Soil quality differences were consistently documented among the three watersheds by: (1) quantification of soil indicator variables, (2) calculation of soil quality index values, and (3) comparison of indicator variable and index results with independent assessments of soil function endpoints (i.e. sediment loss and crop yield). We also used terrain analysis methods to evaluate differences in soil parameters among five landform element classes within the three watersheds. Soil quality differences under ridge-till were found specifically at the backslope and shoulder positions, suggesting that soil quality increases in these positions on the landscape are responsible for higher watershed-scale soil quality in the ridge-tilled watershed.

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